5x1 Linear Antenna Array for 60 GHz Beam Steering Applications

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Abstract— **This paper presents a design process and simulation results of a 5 x 1 linear antenna array with phase shifters for 60 GHz beam steering applications. The antenna array has been designed using a membrane process in order to achieve high radiation efficiency and good radiation characteristics. The same process can be used to manufacture Micro-Electro-Mechanical Systems (MEMS) switches and phase shifters. The maximum gain of the developed antenna array is 9.0 dBi and the radiation efficiency is 87 %. The array consists of 5 equally spaced monopole antennas which each has a gain of 3.2 dBi. The reflection coefficient of the antenna elements is better than -13.5 dB at the desired frequency range from 57 to 64 GHz and the minimum isolation between the adjacent antenna elements is 10.4 dB. The phase shifter which is used for steering the beam of the antenna array has been implemented with MEMS switches and switched transmission lines. The phase shifter enables a phase shift from -80° to +80° by 20° steps. The losses of the phase shifters are less than 2 dB. The results reveal that the membrane technology is a good option for implementing beam steering antenna systems for 60 GHz communications applications.**

I. Introduction

Multiantenna techniques such as Multiple-Input and Multiple-Output (MIMO) and beam steering can be used to increase data transmission rates or reliability of wireless communications systems [1]. The beam steering has been considered as one of the key technologies for 60 GHz communication e.g. by the IEEE 802.11ad standardization working group. It has two advantages compared to single antenna systems: increased gain due to use of antenna array and possibility to reduce interference by steering the beam to the desired direction. Drawbacks are increased complexity and power losses in the phase shifters and antenna array feeding structure. The phase shifters are used for steering the beam of the antenna array. Several phased antenna array designs have been already introduced in the literature for 24 GHz in [2], and for 60 GHz in [3] - [5]. In [2] the phase shifting is done in LO domain. In [3] the phase shifters have been realized with a Butler matrix network, in [4] with a Rotman lens and in [5] with Micro-Electro-Mechanical Systems (MEMS) technology.

At millimeter wave frequencies antennas which are manufactured on normal substrate materials have often low radiation efficiency and poor radiation properties. This is mainly due to surface waves which store energy inside the substrate and losses of the substrate. The efficiency of the antenna can be increased by replacing the substrate with a thin membrane layer. The use of membrane provides reduction of losses, dispersion effects as well as suppression of higher order substrate modes. In addition, the manufacturing costs of the membrane processed antennas are relatively low. Previous designs using membrane structure are Yagi-Uda antennas for 60 GHz and 77 GHz frequency ranges [6], membrane-supported end-fire antennas for 45 GHz [7] and membrane-supported double folded slot antennas for 60 GHz [8]. This paper combines beam steering techniques and a membrane supported antenna array for the first time at 60 GHz. The antenna array has been designed to operate at the unlicensed frequency band from 57 to 64 GHz for short range very high data rate communications applications.

The remainder of the paper has been organized as follows; Section II presents the structure of the designed antenna array together with a short description of the membrane process which can be used to manufacture the antenna array. The phase shifters and the feeding network are presented in Sections III and IV, respectively. Finally, the simulation results of the antenna array are given in Section V.

II. Antenna Array

The structure of the 5x1 linear antenna array is presented in Fig. 1. The array consists of 5 equally spaced monopole antennas which are fed by coplanar waveguides (CPW). The array has been designed on a 20 µm thick benzocyclobutene (BCB) membrane. The characteristic impedance of the CPW and the monopoles is 50 Ω. The array has been designed so that the total surface area of the membrane would be 35 mm^2 which is the maximum size for the manufacturing process. The thin membrane area is surrounded by a 500 µm thick High Resistive (HR) silicon wafer. The thick HR silicon wafer

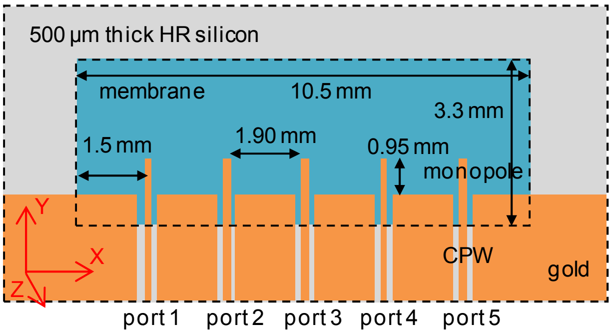


Fig. 1. Dimensions of the 5x1 linear antenna array and a coordinate system.

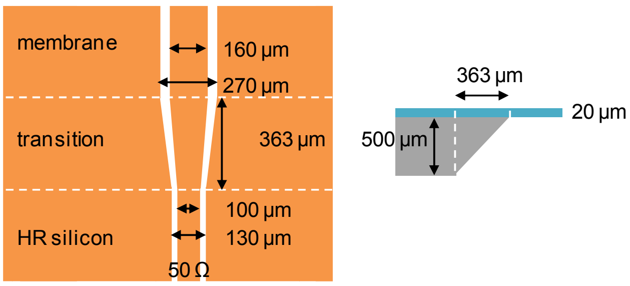


Fig. 2. The dimensions of the CPW and the transition from the thick silicon to the membrane.

has an impact on the radiation properties of the antenna array and it has been taken into account in the simulations.

The dimensions of the antenna array have been optimized with HFFS 3D full-wave electromagnetic field simulation tool. First, the characteristic impedance of the CPW was selected and the dimensions of the CPW were optimized. The same CPW dimensions have been used for the phase shifters and the feeding network. At the edge of the membrane the dimensions of the CPW has to be changed in order to maintain the constant characteristic impedance. The dimensions of the CPW and the transition from the thick silicon substrate to the membrane have been presented in Fig. 2.

The length of the monopole was tuned so that the resonance frequency of the antenna element is 60.5 GHz which is the center frequency of the desired frequency band. Simulations revealed that the optimum length of the monopole is 0.95 mm corresponding approximately 0.19 times of the wavelength in the free space at 60.5 GHz.

The antenna characteristics change when five antennas are placed close to each other. This is due to mutual coupling between antenna elements which change the matching and the radiation properties of the antenna array. The mutual coupling is dependent on the inter-element spacing which has also strong impact on the group radiation pattern of the antenna array. Larger inter-element spacing leads to lower mutual coupling, but on the other hand, the side lobe level starts to increase when the inter-element spacing exceeds 0.5 times the wavelength. It was found from the simulations that the best radiation pattern for the beam steering applications is achieved

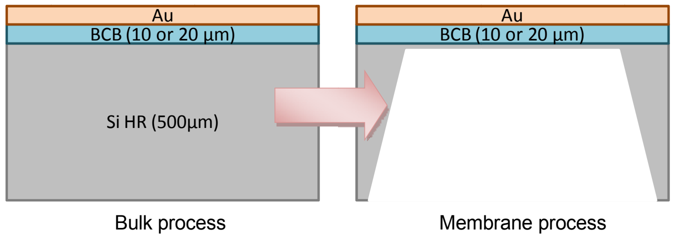


Fig. 3. Membrane process.

when the inter-element spacing equals to two times the length of the monopole i.e. 1.90 mm. The selected value leads to a low side lobe level and, on the other hand, the mutual coupling remains sufficiently low.

The BCB membrane process used for designing the antenna array is presented in Fig. 3. First, a 20 µm thick BCB layer is deposited on the clean HR silicon substrate. After this, a 1.8 µm thick electroplating gold layer is grown on top of the BCB layer. Finally the thick HR silicon substrate is removed from the desired locations using Potassium Hydroxide (KOH) etching as it is shown in Fig. 3. The walls of the substrate are not vertical and this has to be taken into account in the simulations. The angle of the walls is approximately 54º. More detailed description of the membrane process can be found from [9].

The membrane process allows also manufacturing of air bridges using MEMS technology. These air bridges were used to connect ground planes of the CPWs to compensate potentials between ground planes at the intervals of a quarter wavelengths.

III. Phase Shifter

The digital phase shifter has been implemented with the switched delay-line technique and parallel MEMS switches. The membrane process described in Section II allows not only the membrane but is also a MEMS process. Therefore, the phase shifters can be manufactured with the same process as the antenna array. The structure and dimensions of the parallel MEMS switch are presented in Fig. 4. The simulated insertion loss and return loss of the switch are 0.62 dB and 13.2 dB, respectively. The isolation of the switch is 31.3 dB and the actuation voltage is 43.8 V.

The structure of the phase shifter with 9 different phase shifts is presented in Fig. 5. The locations of the switches are marked by green boxes and letters “SW”. The phase shift goes

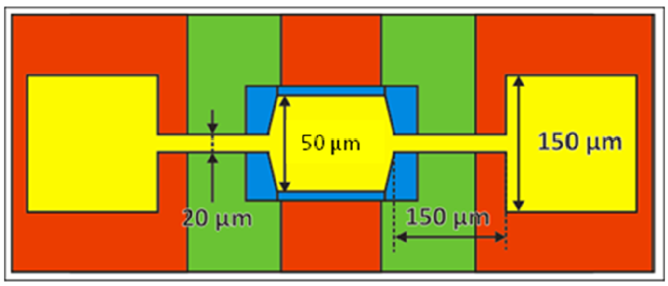


Fig. 4. Parallel MEMS switch.

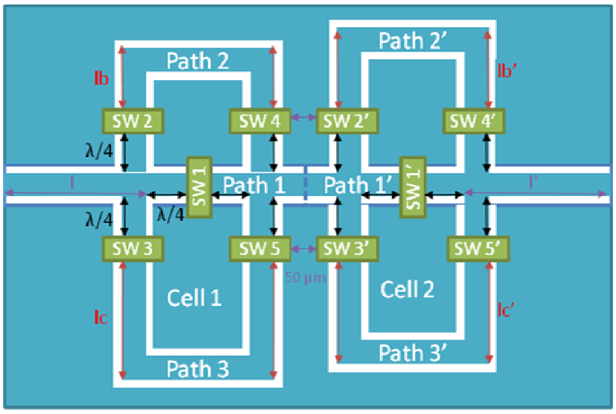


Fig. 5. Structure of the phase shifter.

TABLE I
LENGTH OF THE PATHS IN THE PHASE SHIFTERS.

Length	Phase (°)	Length in λ	Path
1	-80	7/9 λ	L2;L2'
2	-60	5/6 λ	L2;L1'
3	-40	8/9 λ	L2;L3'
4	-20	17/18 λ	L1;L2'
5	0	λ	L1;L1'
6	20	19/18 λ	L1;L3'
7	40	10/9 λ	L3;L2'
8	60	7/6 λ	L3;L1'
9	80	11/9 λ	L3;L3'

from -80° to +80° by 20° steps and each phase shift value corresponds a path in the phase shifter, as given in Table 1. The maximum simulated insertion loss of the phase shifter is below 2 dB. The dimensions of the switch and the phase shifter were optimized with HFSS. Interested readers are referred to master's thesis of Diane Titz [10] for the detailed description of the phase shifters and the MEMS switches.

IV. FEEDING NETWORK

In order to verify the simulation results with measurements the performance of the antenna array has to be measured separately without the phase shifters. For this purpose, a feeding network was designed so that all the antennas can be fed in phase and with the same amplitude. The most reliable option would be to use Wilkinson power dividers for the feeding network. However, because the membrane process has only one layer of metallization it does not allow resistance design which would be needed for the Wilkinson dividers. The only option would be to use chip resistors but at 60 GHz it is very difficult to solder these components. Therefore, basic power dividers will be used which are less lossy compared to the Wilkinson dividers, but on the other hand, they are more sensitive to reflections from the antenna array. Any problem in the matching of the antenna elements will considerably impact the performance of the feeding network. The basic structure of the feeding network is presented in Fig. 6. The characteristic impedances of the transmission lines which lead

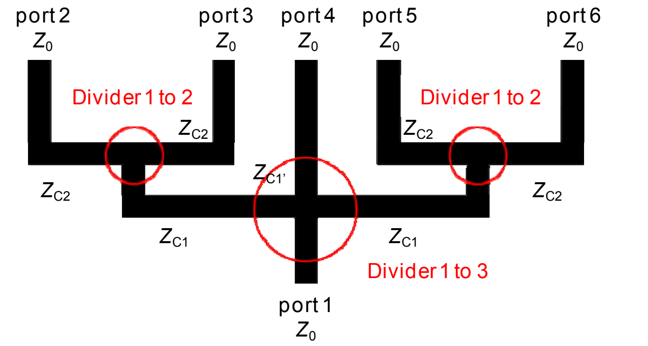


Fig. 6. Feeding network from 1 to 5 ports.

to equal powers in the antenna ports are Z_0 = 50 Ω, Z_{C1} = 56 Ω, $Z_{C1'}$ = 112 Ω and Z_{C2} = 50 Ω. Equations for defining the impedance values can be found e.g. from [11]. The structure of the feeding network was simulated using HFSS and ADS simulation software. The feeding network has an average insertion loss of 9 dB for all the ports and a reflection coefficient of -14 dB across the 57-64 GHz frequency band. The power losses of the feeding network are acceptable for the radiation pattern measurements.

V. SIMULATION RESULTS OF THE ANTENNA ARRAY

This section presents the simulated scattering parameters and the radiation characteristics of the designed antenna array. First, the radiation pattern has been presented without any phase shift, and then with different phase shift values in order to demonstrate the beam steering feature.

A. Single antenna element

The reflection coefficient of the monopole antenna element is -20.5 dB or smaller at the desired frequency range from 57 to 64 GHz. The maximum total gain of the single monopole is 3.2 dBi at the center frequency and the simulated radiation efficiency is 90%.

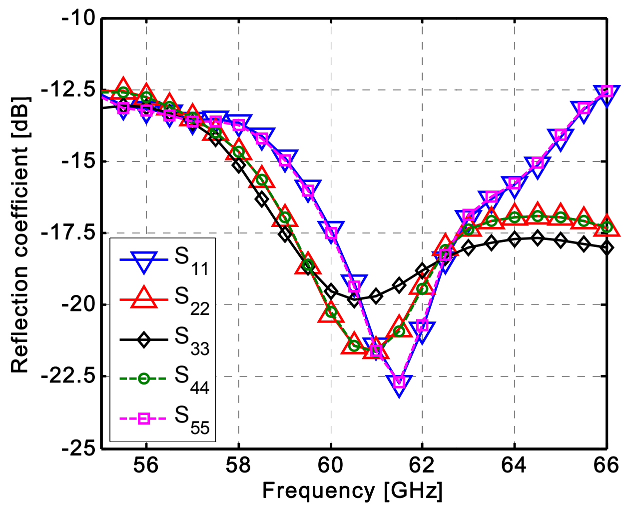


Fig. 7. Simulated reflection coefficients of the 5x1 linear antenna array.

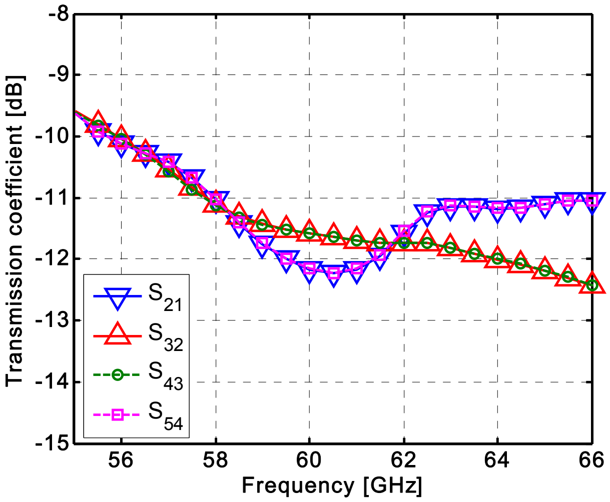
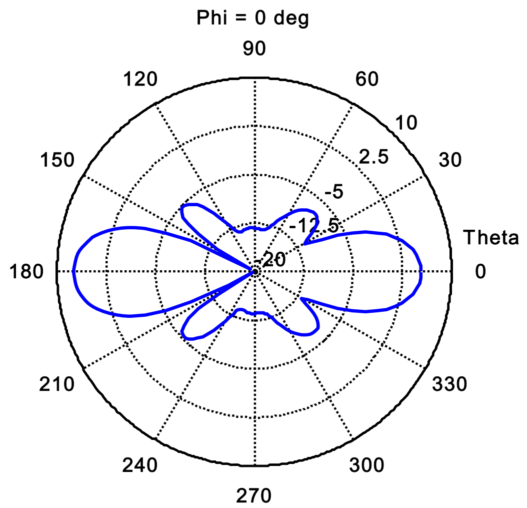
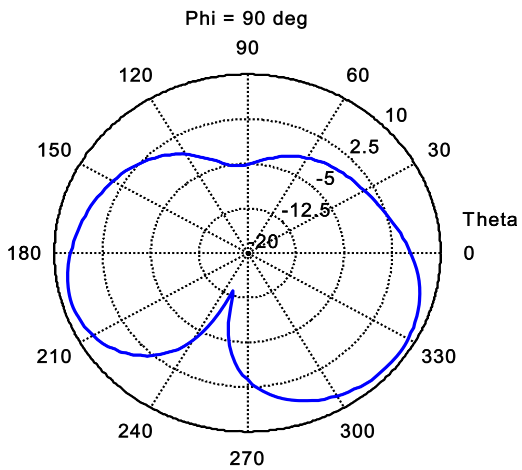


Fig. 8. Simulated transmission coefficients between adjacent antenna elements.



(a)



(b)

Fig. 9. Total gain patterns of the 5x1 antenna array in (a) the XZ-plane (phi = 0°) and (b) the YZ-plane (phi = 90°).

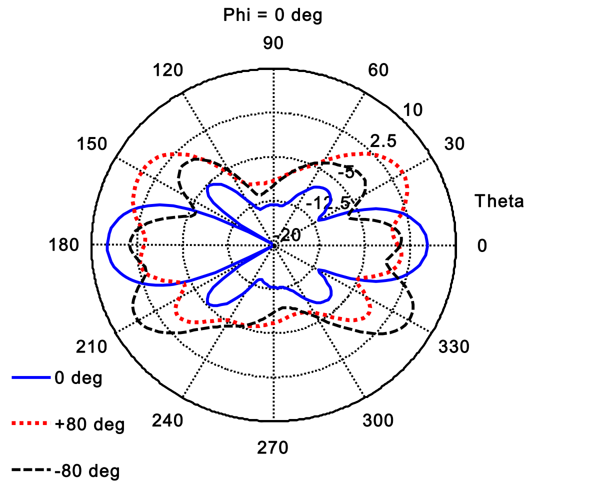


Fig. 10. Total gain patterns of the 5x1 antenna array in the XZ-plane (phi = 0°) with three different phase shift values.

B. Antenna array with phase shifters

The simulated reflection coefficient for each antenna element of the 5x1 linear antenna array are shown in Fig. 7. The matching is better than -13.5 dB at the desired frequency range. The minimum isolation between the adjacent antenna elements is 10.4 dB as shown in Fig 8. The isolation was tried to improve by adding wave traps between the antenna elements. However, adding the wave traps lead to worse matching and it was decided to leave them out from the design.

The radiation pattern of the antenna array is presented in Fig. 9 when all the ports are fed in phase. Normally, the maximum radiation direction of the linear antenna array would be towards the Z-axis but the surrounding substrate material tilt the radiation pattern towards the Y-axis. Also this finding indicates how important it is to take into account the supporting substrate in the design process and simulations. The maximum total gain of the antenna array is 9.0 dBi and it is achieved when $\theta = 330°$ and $\varphi = 90°$. The coordinate system is presented in Fig. 1.

The radiation patterns of the antenna array with three different phase shift values are presented in Fig. 10 for the XZ-plane. The phase shifter enables a phase shift from -80° to +80° with 20° steps. The beam of the antenna array can be tilted ±30° and the maximum variation of the total gain level is less than 3 dB at this angle range.

VI. Conclusions

In this work a 5x1 linear antenna with phase shifters has been designed for 60 GHz beam steering applications. The antenna array has been designed using the membrane technology in order to achieve high radiation efficiency and good radiation characteristics. The matching of the antenna elements is better than -13.5 dB and the minimum isolation between the adjacent antenna elements is 10.4 dB at the desired frequency range from 57 to 64 GHz. The maximum total gain of the antenna array is 9.0 dBi and the radiation efficiency is 87 %. The phase shifters designed for the antenna array enable a phase shift from -80° to +80° with 20° steps. The beam steering feature was demonstrated by showing the radiation pattern of the antenna array with different phase shift values. The beam steering antenna array will be manufactured and the performance of the prototype will be verified with measurements in the future.

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